A NOVEL MINIATURE PLANAR INDUCTOR

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ABSTRACT

The conventional inductor consists of cores and wound wires, which are obstacles for the integration with other devices. The planar inductor, which has planar coils and magnetic layers in place of cores and wires, is fabricated on a substrate. Therefore it can be integrated with other devices, and it will be a fundamental element for the future magnetic IC. In this paper two kinds of planar inductors are described. One is the outer type, which has the larger inductance than any other planar inductor. The other is the inner type, which has the possibility for a variable inductor.

1. INTRODUCTION

The integration of inductors on magnetic IC's has lagged far behind that of other devices. A few reports have been heard on the integration of inductors. Firstly a core and a spiral type were proposed[1]. Secondly we have proposed the planar inductors, which are miniature inductors with magnetic layers, planar coils and insulators, and fabricated by thin-film and photo-etching technique[2]. In a meander type the inductance is $1(nH/mm^2)$ and suitable for high frequency above 100(MHz). Thirdly insulators were removed[3]. The inductance shows a flat response till 400(MHz).

Two planar inductors with two spiral coils are proposed. As two coils are connected with the coupling factor positive, the inductance becomes much larger. On the other hand as coils are connected negatively, the inductance becomes much smaller. But it depends on the magnetic layer.

2. PLANAR INDUCTORS WITH TWO SPIRAL COILS

2.1 COIL CONNECTIONS

Two type planar inductors with two spiral coils are conceived. The over views are shown in Fig.1. One

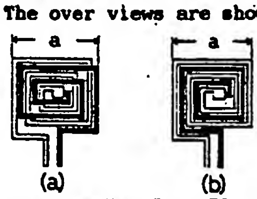

Fig.1 Over Views of Two Type Planar Inductors with Two Spiral Coils
(a) Outer Type (b) Inner Type

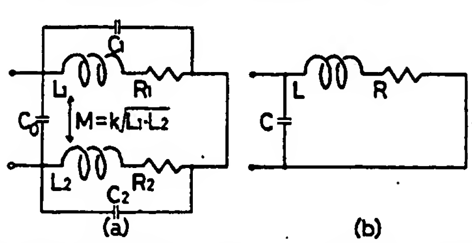

Fig.2 The Equivalent Circuit of Planar Inductors
(a) With Two Coils (b) With One Coil
L, L_1, L_2:self inductance M:mutual inductance
R, R_1, R_2:coil resistance k:coupling factor
C, C_0, C_1, C_2:stray capacitance

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has two coils that are connected with the mutual inductance positive. We call it the outer type. The other has coils that are connected negatively. We call it the inner type. Fig.2(a) represents the simple equivalent circuit. The characteristics are measured on the assumption that the inductance and the resistance are connected in series and the stray capacitance is parallel to them as shown in Fig.2(b).

2.2 THE OUTER TYPE

The schematic view of the outer type is shown in Fig.3(a). As seen in Fig.3(b) the magnetic field due to the coil current encloses the entire coils. So the magnetic layers are deposited to sandwich the coils as

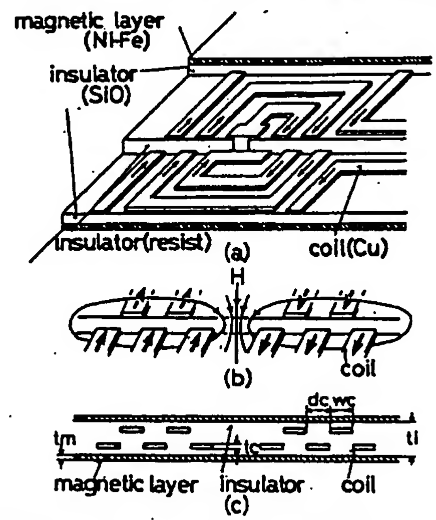

Fig.3 The Outer Type Planar Inductor
(a) Schematic View
(b) Magnetic Field due to the Coil Current
(c) Cross Sectional View

shown in Fig.3(c). The inductance is expressed in (1), where a is coil size; wc=width of the coil; tm=thickness of the magnetic layer; ti=thickness of the insulator. The distance between adjacent coils dc becomes equal to wc for each coil not to overlap. N is number of spiral turns of each coil, and b is the length defined as a-4Nwc. The relative permeability of the magnetic layer is expressed as μr.

$$L_o(s)=\frac{4\sqrt{2}\,N\cdot\mu_0\cdot b^2}{\pi}\sum_{i=0}^{2N-1}\left[\frac{1}{a-(2i+1)wc}\right]$$

$$+N^2\cdot\mu_0\cdot b\sqrt{\frac{2a}{N\cdot wc}}+\frac{2N^2\cdot\mu_0}{\dfrac{tm+ti}{b^2}+\dfrac{N\cdot wc}{\mu r\cdot tm(a+b)}} \quad (1)$$

$$C_o(s)=3(2N-1)\,\epsilon\frac{wc^2}{ti-2tc}+12N\cdot\epsilon\frac{wc}{ti-2tc}(a-2N\cdot wc) \quad (2)$$

$$R_o(s)=8N\cdot\rho\frac{a-2N\cdot wc}{wc\cdot tc} \quad (3)$$

The first and second terms are determined only by the shape and size of coils, and the last depends on the permeability of magnetic layers. The stray capacitances are given in (2), where ϵ is permittivity

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of the insulator. The former exists between the two coils, and the latter exists between the coils and the magnetic layers. The coil resistance is shown in (3), where tc is thickness of the coil, and p is resistivity of the coil. Eq.(3) does not include losses due to skin effect and eddy current. For high frequency band, the resistance increases mainly by eddy current loss.

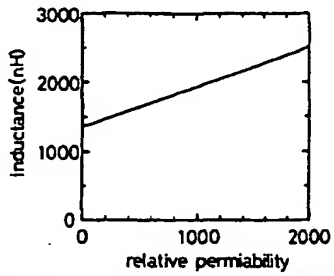

Fig.4 The Relation between the Calculated Inductance and the Permeability of the Outer Type
a=9.2(mm), wc=0.2(mm), tm=0.5(μm), ti=10(μm), N=8

The relation between the calculated inductance and permeability is shown in Fig.4(a=9.2(mm), wc=0.2(mm), tm=0.5(μm), ti=10(μm), N=8). The inductance for μ_r=1 is 1300(nH). But the inductance for μ_r=2000 is only 2 times as large as for μ_r=1. The reason is as below. The flux of the outer type is distributed around the coils. As thickness of the inductor is much smaller than its area, most flux leaks from the magnetic layer to space.

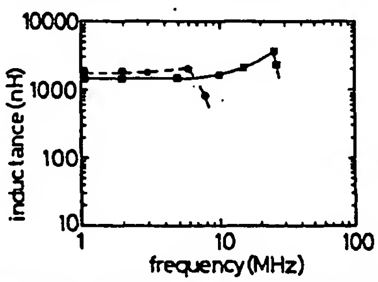

Fig.5 Frequency Characteristics of the Outer Type
——■—— no magnetic layer
- - -●- - - with magnetic layer
a=9.2(mm), wc=0.2(mm), tc=1.5(μm), tm=0.5(μm), ti=8(μm), N=8, μ_r=200

The frequency characteristics of the practical inductance are shown in Fig.5(a=9.2(mm), wc=0.2(mm), tc=1.5(μm), tm=0.5(μm), ti=8(μm), N=8, μ_r=200). Without the magnetic layers the inductance is 1670(nH) at 1(MHz) and in rough agreement with the calculated value. The frequency where the inductance is maximum f_{LMAX} is about 20(MHz). By the magnetic layer addition the inductance increases only to 1800(nH), and f_{LMAX} drops below 10(MHz). The frequency is proportional to $1/\sqrt{LC}$. The magnetic layers, which produce the large capacitance, make f_{LMAX} lower.

2.3 THE INNER TYPE

In the outer type the inductance is mainly determined by the shape and size of coils. The magnetic layer, even if it has high permeability, did not exhibit its characteristics and only contributed to increasing the stray capacitance. So the inner type is proposed to make use of the magnetic characteristics.

$$Li(s)=N\cdot\mu_0\frac{a+b}{wc}\,[tm(\mu r-1)+ti] \tag{4}$$

$$Ci(s)=4N\cdot\varepsilon\frac{wc}{ti-tm}\,(a-2N\cdot wc) \tag{5}$$

$$Ri(s)=8N\cdot p\frac{a-2N\cdot wc}{wc\cdot tc} \tag{6}$$

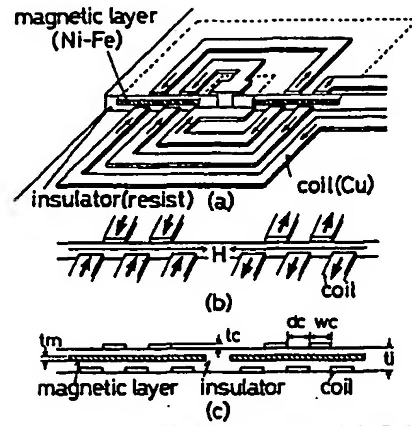

Fig.6 The Inner Type Planar Inductor with Spiral Coils
(a) Schematic View
(b) Magnetic Field due to the Coil Current
(c) Cross Sectional View

The schematic view of the inner type is shown in Fig.6(a). As seen in Fig.6(b) the field due to the coil current is focused between two coils. So the magnetic layer is inserted there as shown in Fig.6(c). The inductance is expressed in (4). Eq.(4) is derived on the following assumptions (see Fig.2(a)).

$$L_1=L_2 \tag{7}$$

$$k=-1 \tag{8}$$

The stray capacitance between the coils and the magnetic layer is given in (5). Without the magnetic layer the stray capacitance is negligibly small because two coils never overlap as seen in Fig.1(b). The coil resistance is given in (6). In Fig.7 the relation between the calculated inductance and permeability is shown(a=9(mm), wc=0.2(mm), tm=0.5(μm), ti=5(μm), N=8). As seen in Fig.7, the inductance for μ_r=1 is very small. Therefore it becomes proportional to μ_r.

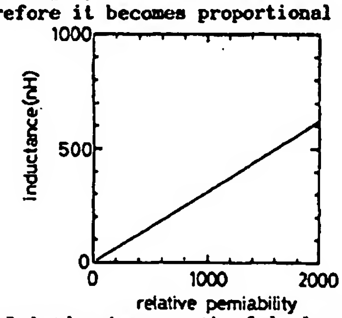

Fig.7 The Relation between the Calculated Inductance and the Permeability of the Inner Type with Spiral Coils
a=9(mm), wc=0.2(mm), tm=0.5(μm), ti=5(μm), N=8

The frequency characteristics of the practical inductance are shown in Fig.8(a=9(mm), wc=0.2(mm), tc=1.5(μm), tm=0.2(μm), ti=5(μm), N=8, μ_r=200). With the magnetic layer the inductance is 100(nH) at 1(MHz) and larger than the calculated value of 61(nH). The frequency characteristic in DC magnetic field H_{DC} is also measured to investigate the effect of the magnetic layer. H_{DC} is 20(kA/m) and the magnetic layer is saturated in it. The inductance in H_{DC} decreases to 55(nH). The inductance becomes twice larger by the magnetic layer. But the inductance in H_{DC} becomes much

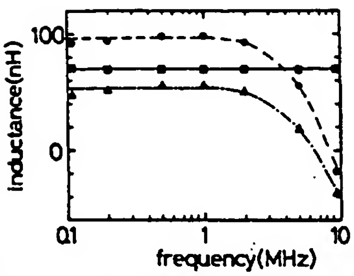

Fig.8 Frequency Characteristics of the Inner Type with Spiral Coils

—■— no magnetic layer

- - -●- - - with magnetic layer

-·-·▲-·-· with magnetic layer in DC field

a=8(mm), wc=0.2(mm), tc=1.5(μm)

tm=0.2(μm), ti=5(μm), N=8, μr=200

larger than expected. The inductor without the magnetic layer is fabricated to examine the inductance for μ_r=1. The inductance is 70(nH) and differs from the calculated. The reasons are as below. Firstly as the size of the upper coil is smaller than that of the lower, L_1 is not equal to L_2. Secondly as coils are slipped off, the coupling factor is low. Thirdly some flux encloses not the entire coils but single one. Eq.(4) can not express the true inductance.

3. A PLANAR INDUCTOR WITH TWO HOOP COILS

As the inner type with two spiral coils had the large resistance and the stray capacitance between the coils and the magnetic layer, this inductor did not operate in the high frequency range. So the inner type is improved by using hoop coils as shown in Fig.9.

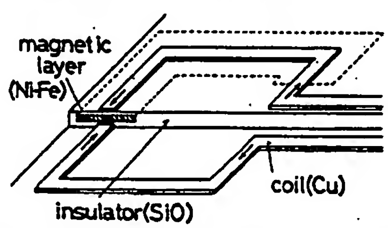

Fig.9 Schematic View of the Inner Type with Hoop Coils

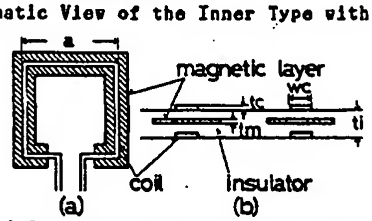

Fig.10 Over and Cross Sectional View of the Inner Type with Hoop Coils

The over and cross sectional view are shown in Fig.10. Two spiral coils are connected at the center of them, while hoop coils are connected outside. As a hoop coil is short, this inductor has the small resistance and the stray capacitance. Two coils are identical, and they are aligned on just opposite sides of the magnetic layer to make the coupling factor high. Its inductance, stray capacitance and coil resistance are given in (9),(10) and (11) respectively.

$$Li(h)=4\mu_0 \frac{a}{wc}[tm(\mu r-1)+ti] \quad (9)$$

$$Ci(h)=4\varepsilon \frac{a\cdot wc}{ti-tm} \quad (10)$$

$$Ri(h)=8\rho \frac{a}{wc\cdot tc} \quad (11)$$

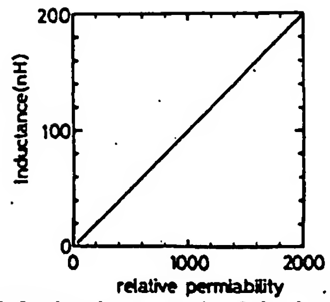

Fig.11 The Relation between the Calculated Inductance and the Permeability of the Inner Type with Hoop Coils

a=8(mm), wc=0.2(mm), tm=0.5(μm), ti=5(μm)

In Fig.11 the relation between the calculated inductance and permeability is shown(a=8(mm), wc=0.2(mm), tm=0.5(μm), ti=5(μm)). The inductance becomes proportional to μ_r just like Fig.7.

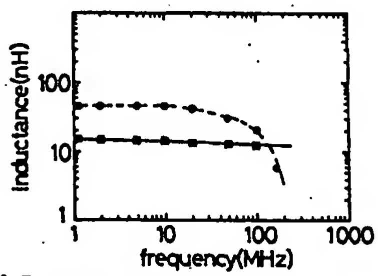

Fig.12 Frequency Characteristics of the Inner Type with Hoop Coils

- - -●- - - no DC field

—■— in DC field

a=8(mm), wc=0.2(mm), tc=1(μm)

tm=0.5(μm), ti=5(μm), μr=350

The frequency characteristics of the practical inductance are shown in Fig.12(a=8(mm), wc=0.2(mm), tc=1(μm), tm=0.5(μm), ti=5(μm), μ_r=350). The inductance is 50(nH) and larger than the calculated value of 35(nH), while in H_{DC} that decreases to 15(nH). The inductance becomes 3 times larger by the magnetic layer, and the ratio is higher than that of spiral coils. But the inductance in H_{DC} becomes much larger than expected. The reasons are as below. Firstly as there is a gap between two coils, the coupling factor becomes low. Secondly a coil has the internal inductance.

4.CONCLUSION

Two type planar inductors with two coils are proposed. The inductance of the outer type is 18(nH/mm²), and 4 times as large as that with single coil. But it hardly depends on the magnetic layer. By the magnetic layer the inductance of the inner type can be changed freely theoretically, and the inductance of the fabricated inductor becomes several times larger.

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